Pushing the limits of laser synchrotron light sources

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National Synchrotron Light Source

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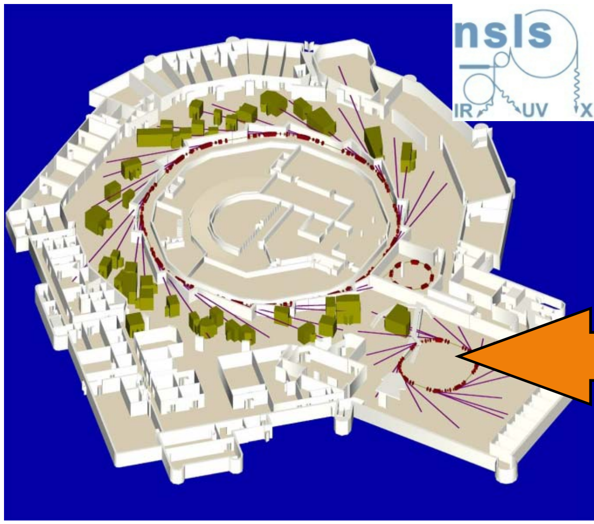
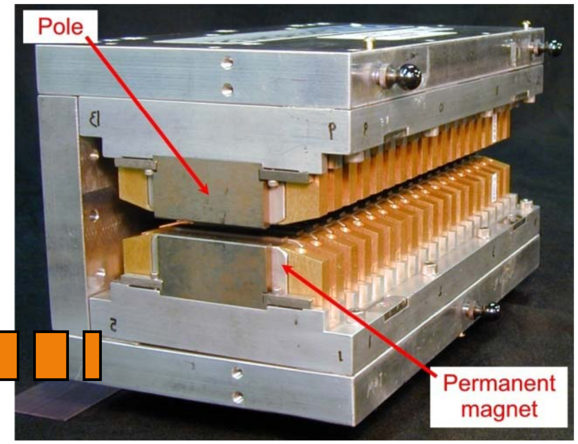
Synchrotron light source





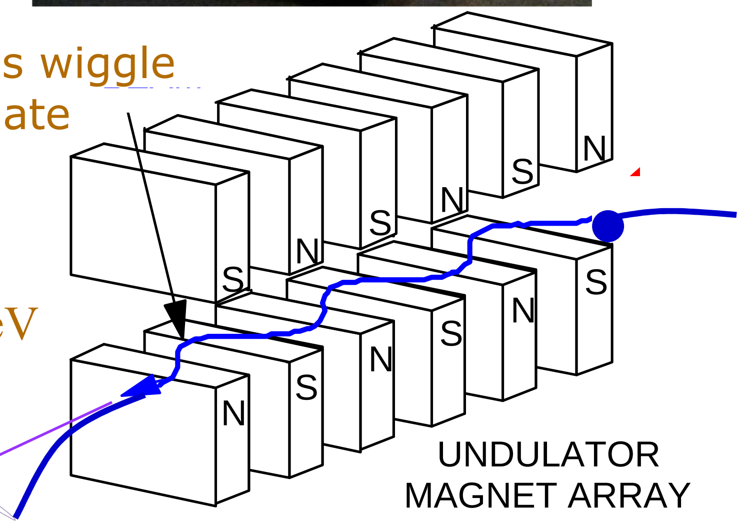
With λ_w ~ several centimeters, attaining XUV region requires electron energy in the GeV region.

Electrons wiggle and radiate

$E_e = \gamma mc^2$
$mc^2 = 0.5$ MeV

X-rays

$\lambda_x = \lambda_w / 2\gamma^2$

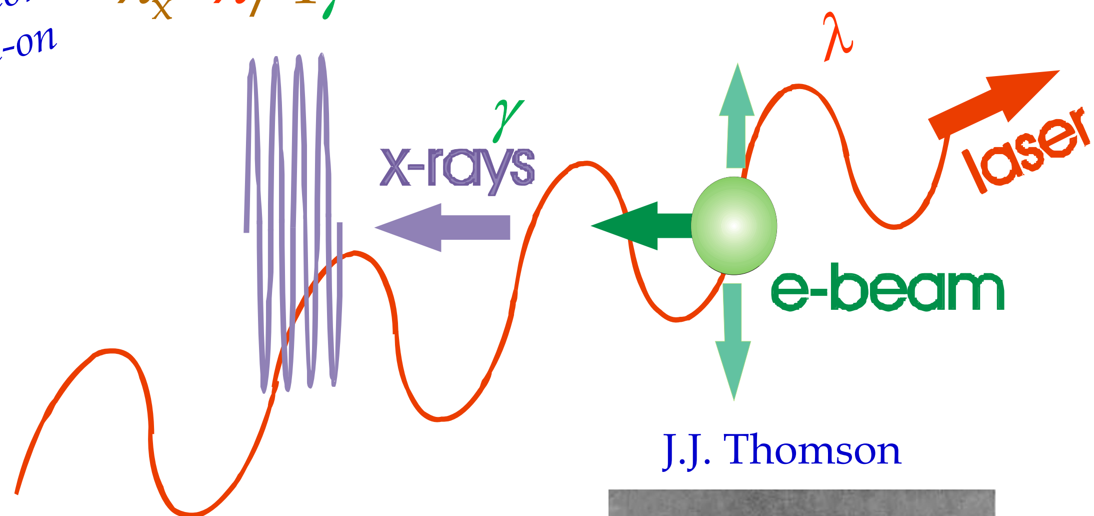


Laser – a virtual wiggler

(same physics as for Thomson scattering)

$$\lambda_x = \lambda / 4\gamma^2$$

Scattered photon satisfies undulator equation with period λ/2 for head-on collisions



Advantages of a <u>Laser Synchrotron Source:</u>

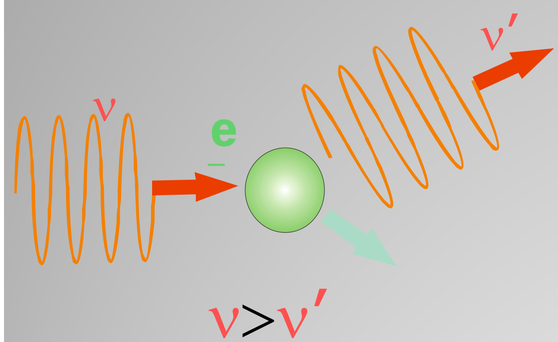
- access to hard-x-ray and gamma regions with a compact linac
- polarization control
- pico- and femto-second pulse length
- ultra-high peak brightness

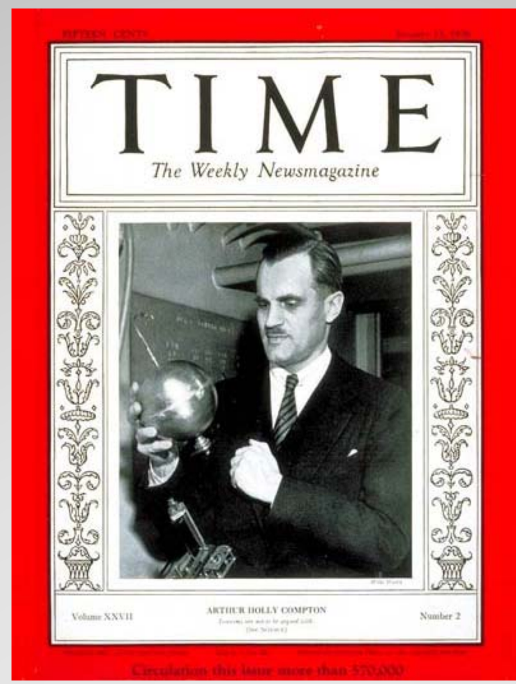
J.J. Thomson

Inverse Compton scattering

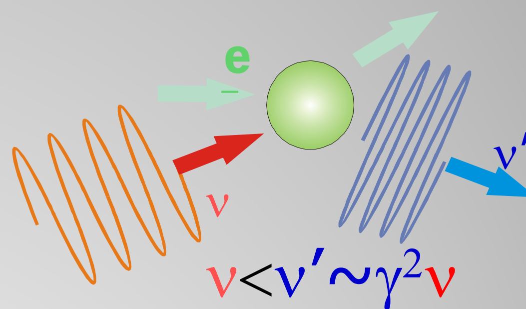
(alternative terminology for the same effect)

Compton scattering





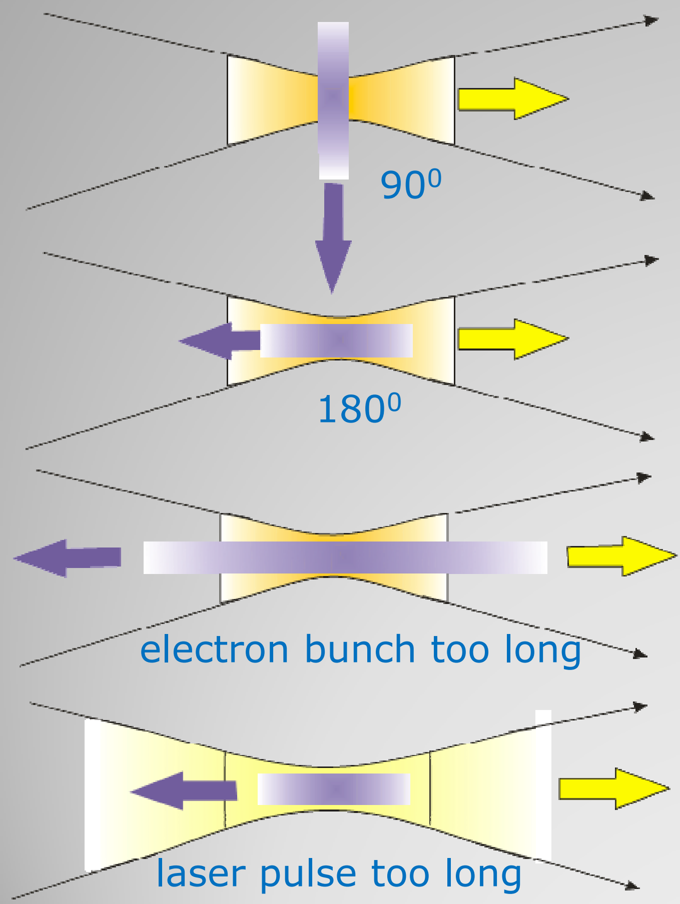
Inverse Compton scattering



Inelastic photons scattering off electrons that are initially at rest. The electron gains energy and the scattered photon has a frequency less than that of the incoming photon.
Noticeable @ $h\nu \sim mc^2$.

Inverse Compton scattering takes place when the electron is moving, and it's kinetic energy is comparable to the scattered photon.
"ICS" terminology more common @ $h\nu' \sim \gamma mc^2$.

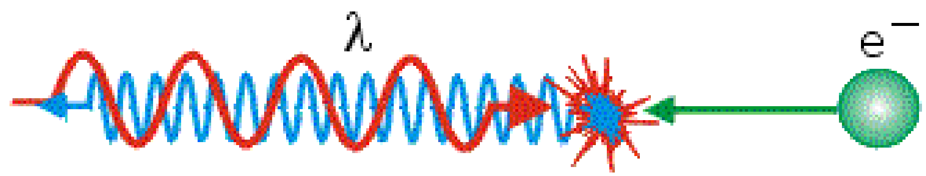
Importance of matching the electron bunch to the laser pulse



- 90-deg interaction reduces x-ray yield dramatically (useful for diagnostic purpose).
- Counter-propagation is the most efficient geometry.
- Comparison of λ with ε_n/γ tells which one, e-beam or laser define the interaction region length.
- Typically, low-emittance electron beam permits much tighter filementation than the laser focus.
- Laser and electron bunch should fit within the Rayleigth range . Optimum condition $\tau_{L,e}c<2L_R$. $L_R=\pi^2 r_L{}^2/\lambda$
- Higher photon density within the interaction region – higher x-ray yield.

Making choice between CO_2 and solid-state lasers

$$N_x = \sigma_T N_L N_e / \pi r_L^2$$



$$\lambda_x = \lambda / 4\gamma^2$$

- 10-μm laser produces 10 times more photons per Joule than 1-μm laser.

- CO_2 laser requires 3 times more energetic accelerator to attain the same λ_x.

However, with CO_2 laser:

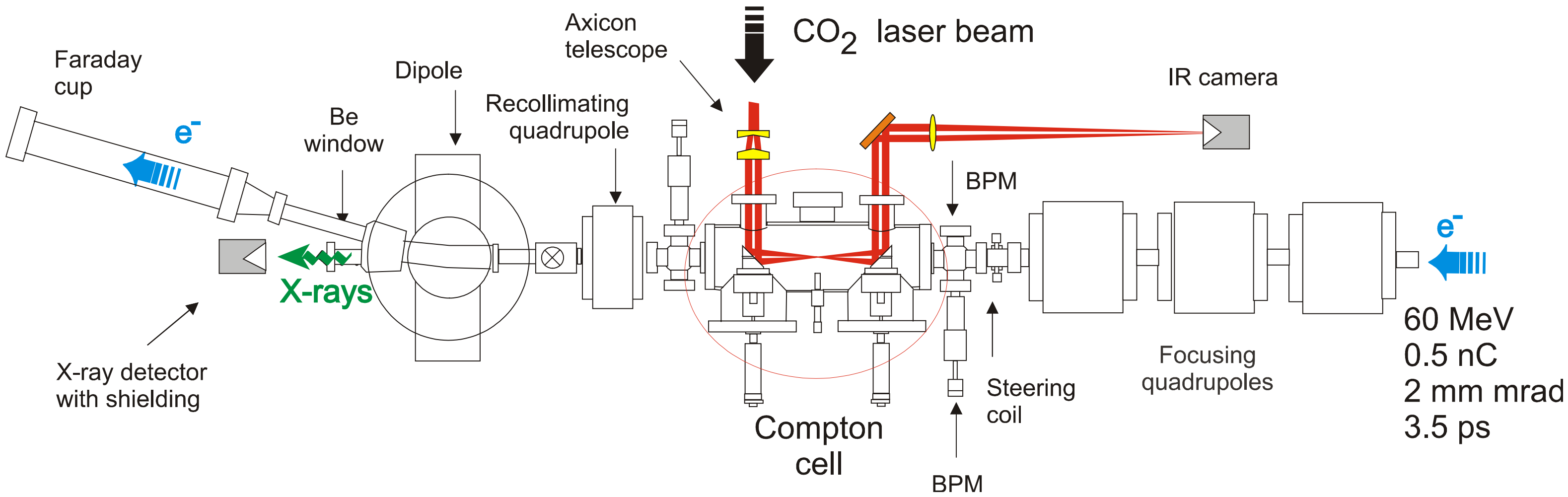
- Angular divergence improves 3 times

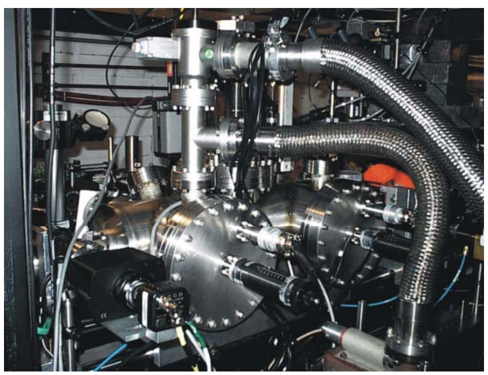
$$\phi = 1/\gamma$$

- Brightness improves 100 times

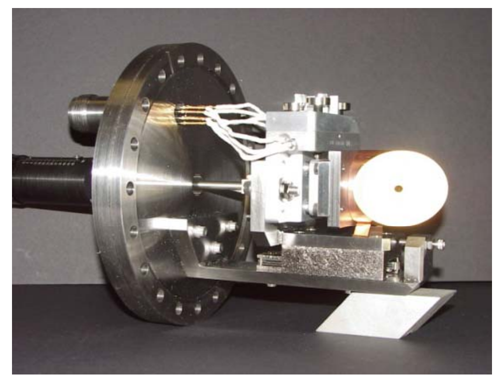
$$B = \underset{\uparrow\ \times 10}{N_x} / 2(\pi \underset{\uparrow\ \times 10}{\phi} r_b)^2 \tau_b$$

BNL Thomson scattering experiment





Laser parameters:
τ= 5 ps,
E = 5 J,
P = 1 TW,
focused to σ = 35 μm,
Demonstrated $N_x/N_{e-} \simeq 1$!



$$\frac{N_x}{N_e} = \frac{N_L}{\pi w_0^2}\sigma_T$$

To compare with 1-μm lasers, CO_2 laser delivers 10× photon number per Joule

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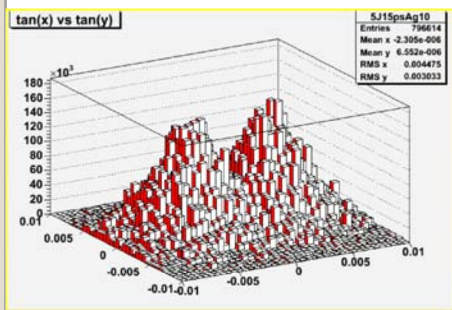
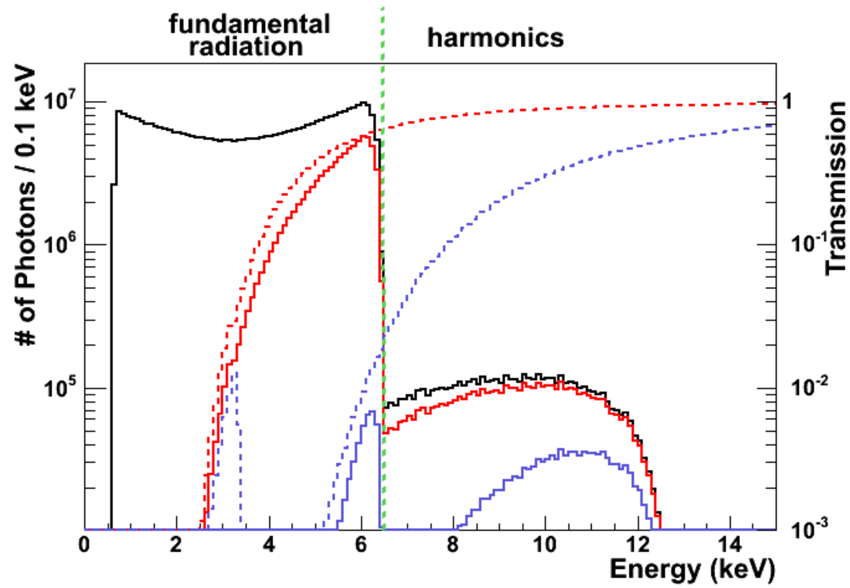
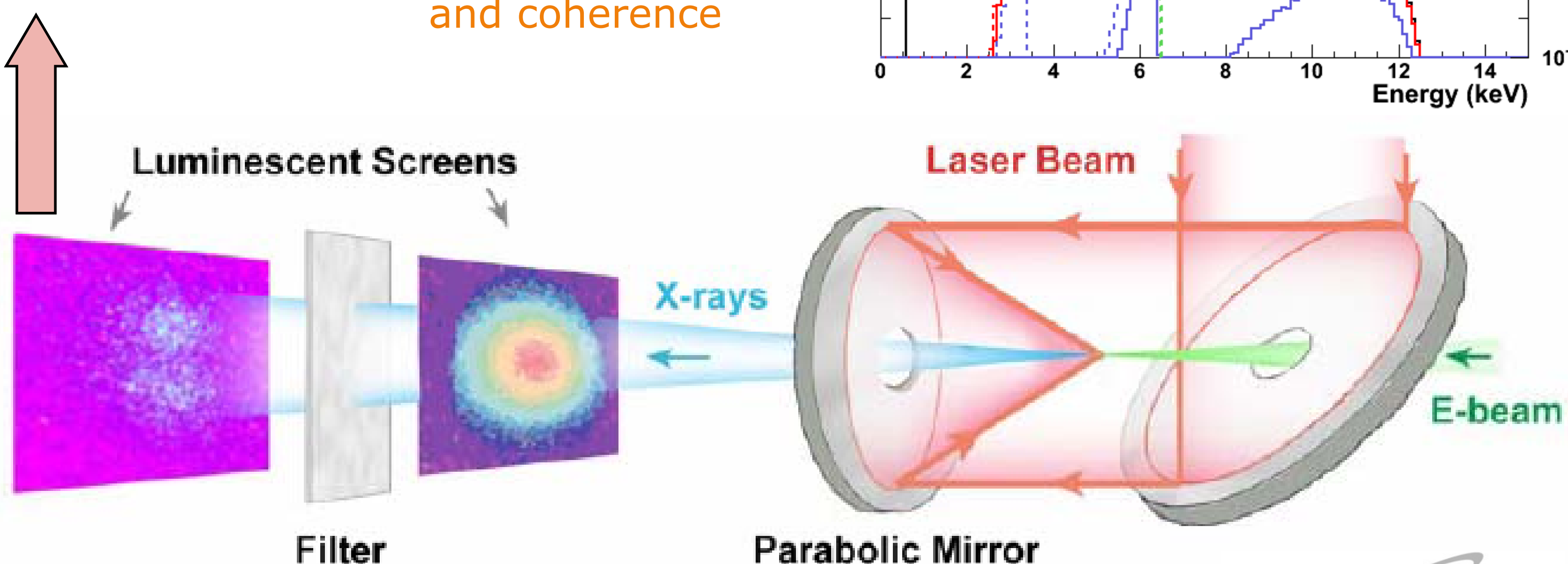
Observation of 2nd harmonic in Thomson scattering



Although fundamentally interesting, nonlinear effect should be avoided when the goal is high monochromaticity and coherence





high-bandpass filter allows to separate harmonics from fundamental

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Thomson wavelength and pulse duration are easy to derive

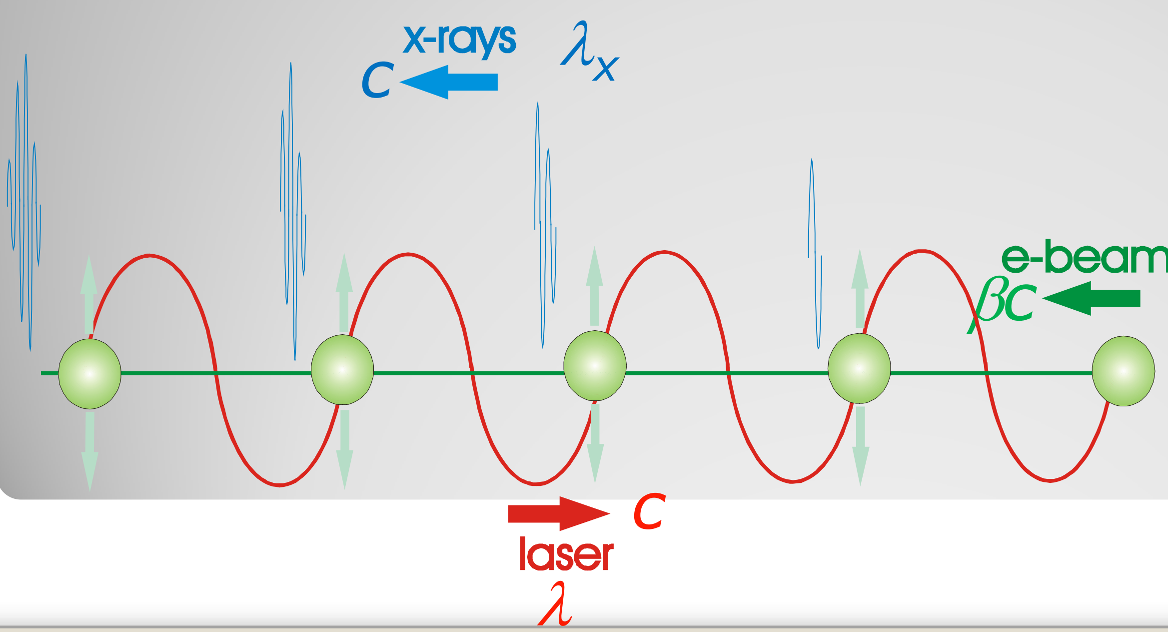
Frequency multiplication due to Doppler effect:

•Photons emerge because electrons move slower than the speed of light.
•One period of the generated wave occupies the interval: $\lambda_x = (1-\beta)\lambda/2 = \lambda/4\gamma^2$

X-ray pulse length:

•Nearly as short as the electron bunch:

$$\tau_x = \tau_b + \tau_l/4\gamma^2$$

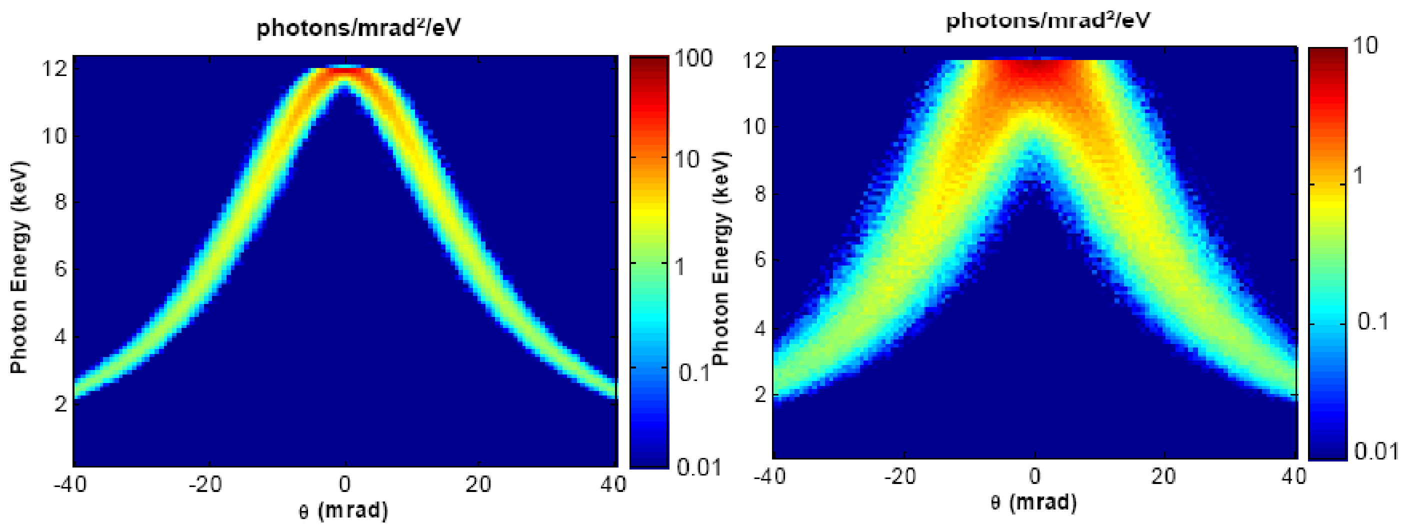


$$\beta = \sqrt{1 - \frac{1}{\gamma^2}} \approx 1 - \frac{1}{2\gamma^2}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

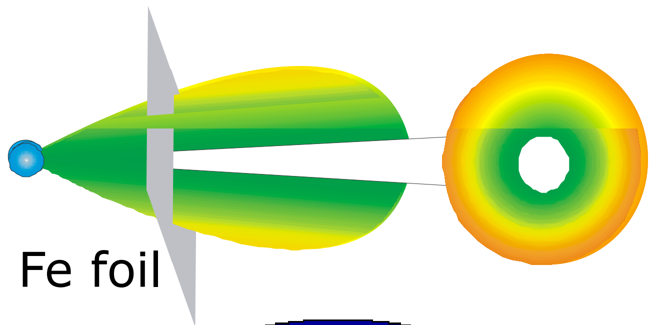
Angular divergence of Thomson spectrum and effect of e-beam emittance

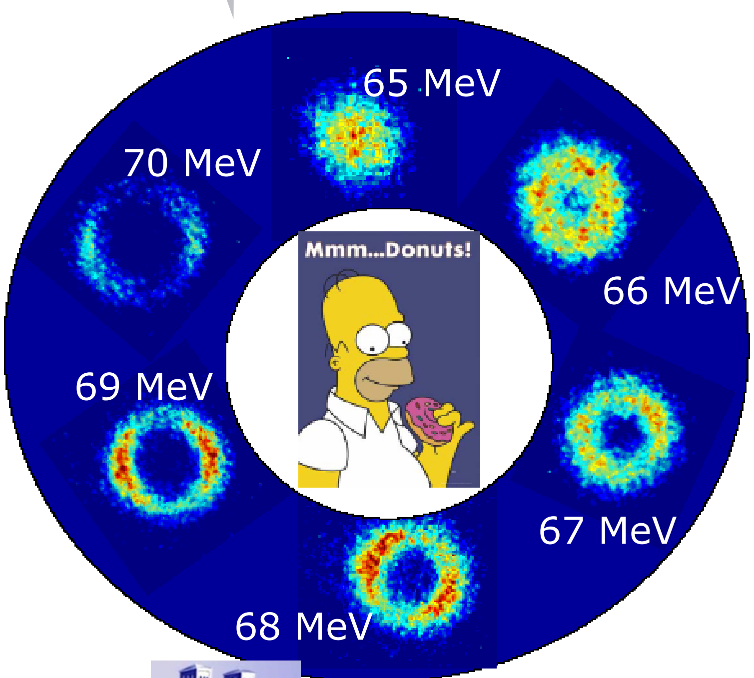
Normalized emittance = 0.3 μm Normalized emittance = 1.0 μm

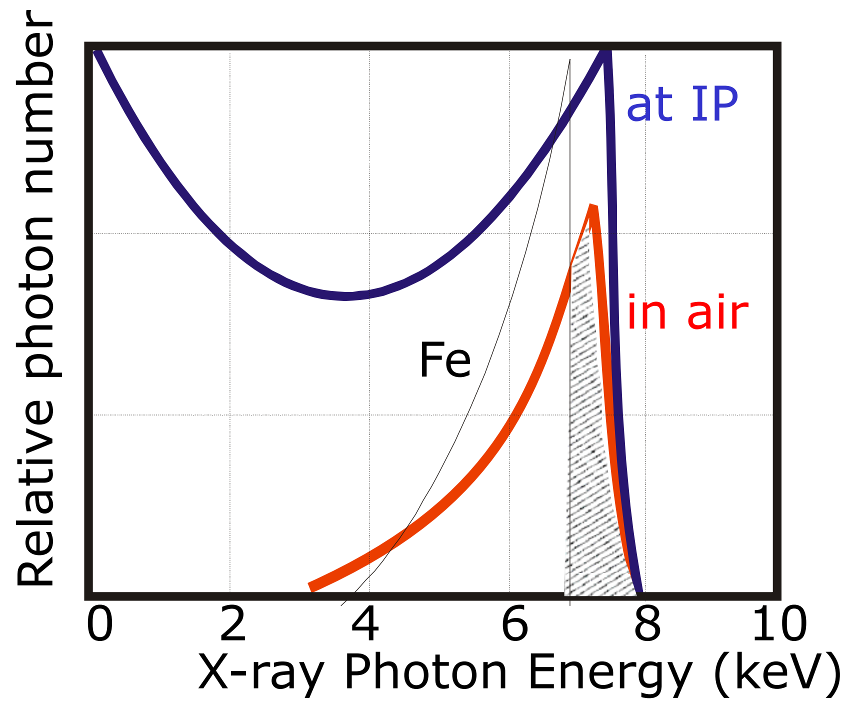


$$\boxed{\omega_x = \omega_0 \frac{4\gamma^2}{1+\gamma^2\theta^2 + a_0^2/2}} \Rightarrow \boxed{\Delta\omega/\omega \approx \Delta\theta^2\gamma^2} \Rightarrow \boxed{\Delta\omega/\omega \approx (\varepsilon_n/\sigma_b)^2}$$

K-edge filter allows to assess x-ray spectrum without spectrometer







- Higher γ => Higher E_x => More photons off-axis above K-edge => Bigger donut hole.
- Small energy spread is critical for high-contrast medical imaging (blood vessels).

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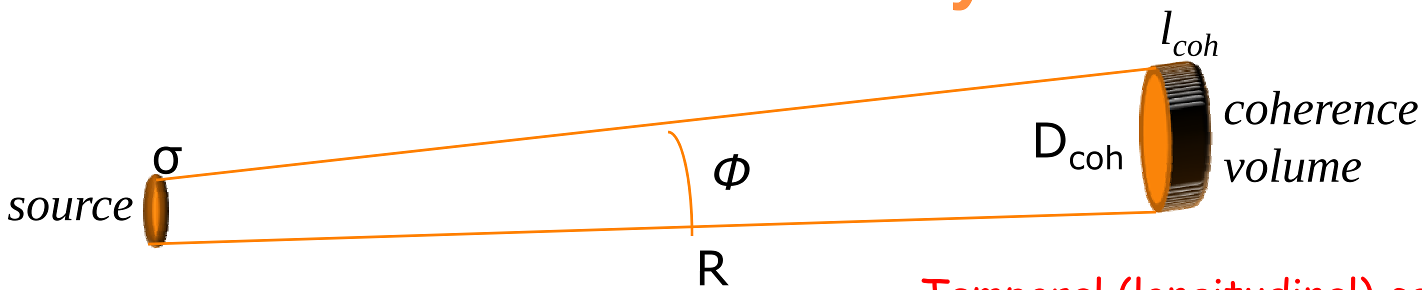
Partial coherence of laser synchrotron sources



Condition for spatial (transverse) coherence

$$\sigma \times \phi \le \lambda_x$$

Example: $\sigma = 100\lambda_x \quad R=1 \text{ m}, \ D=1 \text{ cm}$

Acceptable bandwidth without loss of interference visibility is very broad $\Delta\lambda_x / \lambda_x = 1$

Temporal (longitudinal) coherence

$$\tau_{coh} = \frac{1}{\Delta \nu} \quad \text{or} \quad l_{coh} = \lambda_x^2 / 2\Delta\lambda_x$$

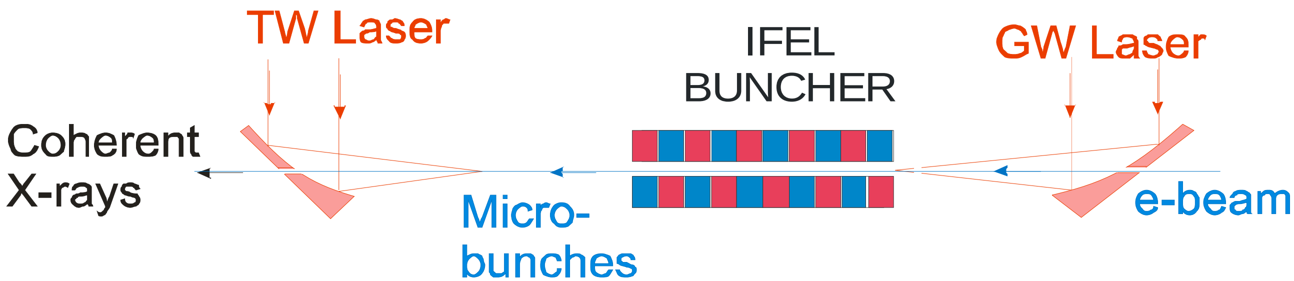
typical coherence length ~μm

Bandwidth limitations on Thomson monochromaticity

- e-beam angular divergence
- number of interacting laser wavelengths N
- momentum spread of the e-beam
- *Typical* $\Delta\lambda_x / \lambda_x$ *numbers between* 10^{-2}-10^{-3}

$$\Delta\lambda'_x / \lambda_x = (\varepsilon_n / \sigma_b)^2$$
$$\Delta\lambda''_x / \lambda_x = 1/N$$
$$\Delta\lambda'''_x / \lambda_x = 2\Delta\gamma/\gamma$$

Microbunched e-beam can produce coherent laser syncrotron radiation



By interacting e-beam with co-propagating CO_2 laser inside a wiggler, we achieved micro-bunching exactly to the laser period. Each micro-bunch 1 μm long.

Interacting such micro-bunches with counter-propagating laser shall result in bursts of temporary coherent 1-μm radiation packets. Synchronized one to another, they ensure temporal coherence of the entire macro-pulse.

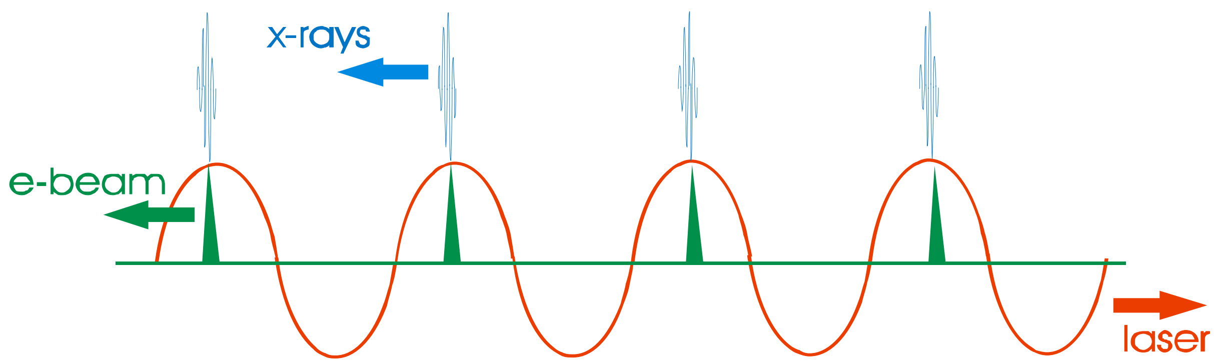


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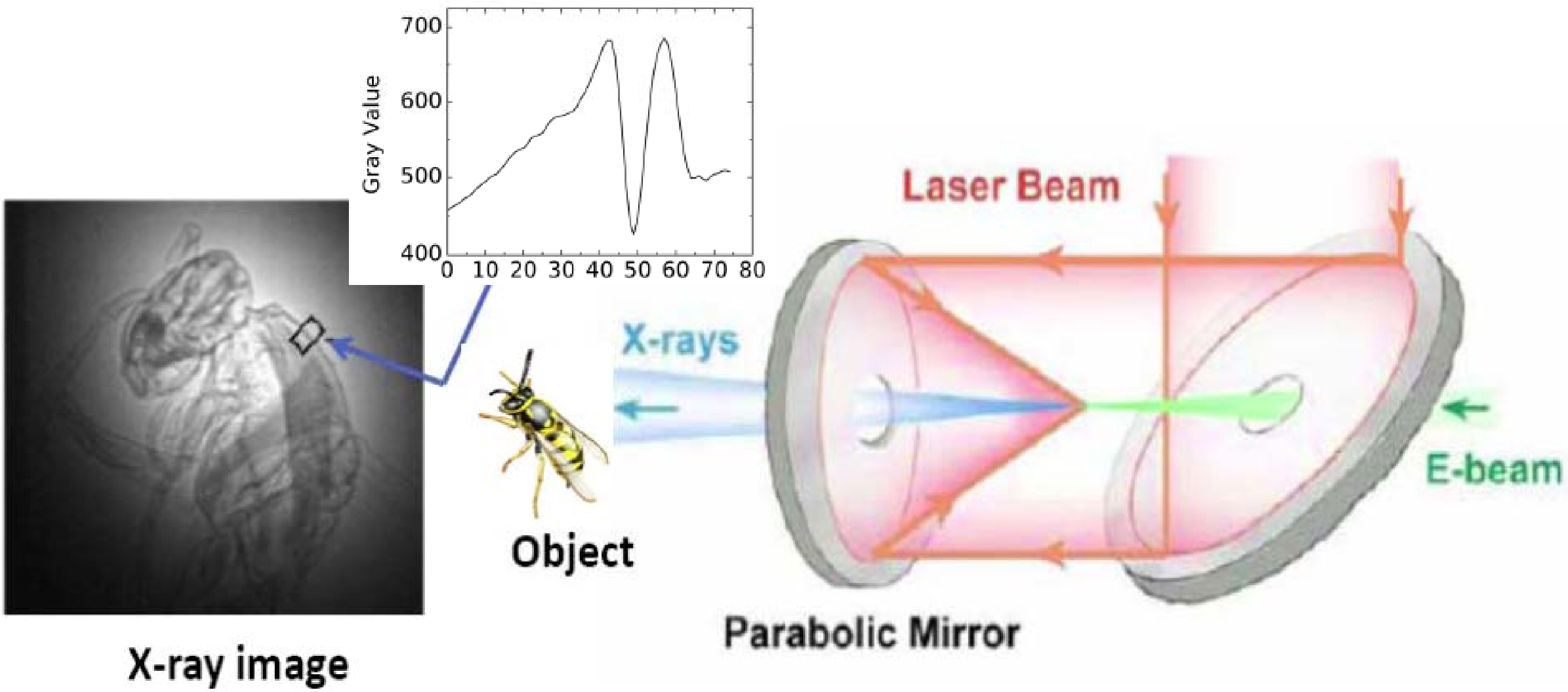
Illustration of spatial coherence: Phase contrast imaging due to interference



Single-shot X-ray image of a wasp with 1-ps exposure

P. Oliva, et al, Appl. Phys. Lett. 97, 134104 (2010).

INFN

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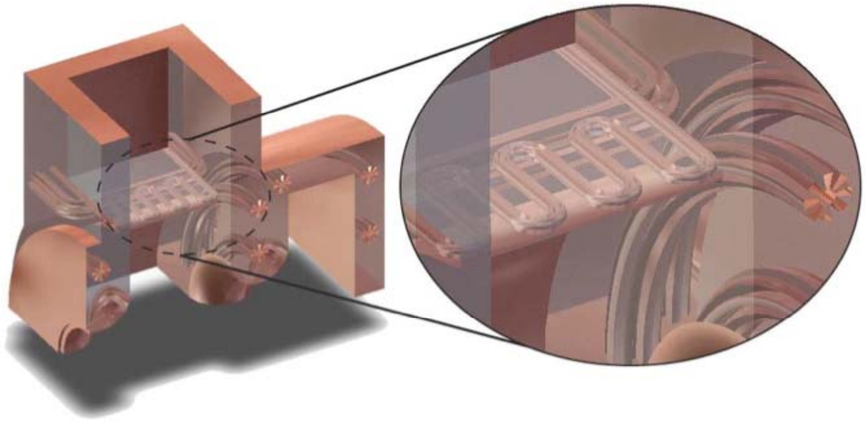
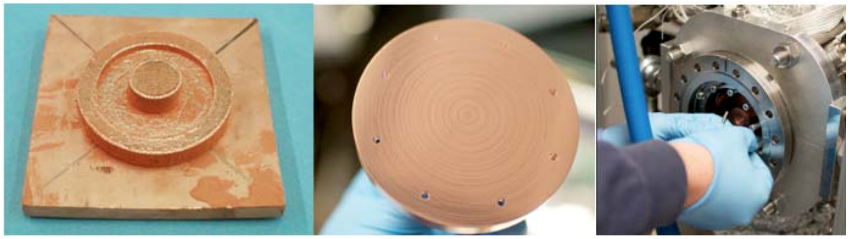
High duty-cycle photoinjectors

- High rep. rate (~ 1kHz), high brightness photoinjector currently being developed at RadiaBeam
  - S-band high brightness gun (RBT-UCLA-LLNL collaboration)
  - Prototype structure scheduled for testing next year at LLNL
- Utilizing layer manufacturing process (freeform fabrication)
  - Enhanced thermal handling capabilities
  - Successful prototype cathode demonstration under high power RF

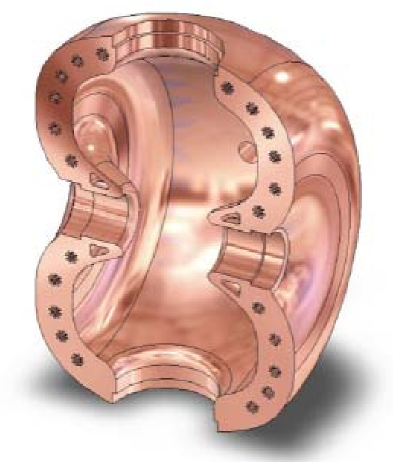
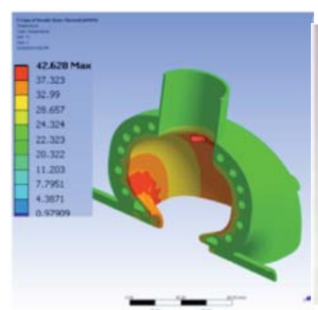




radiabeam TECHNOLOGIES

CW photoinjectors

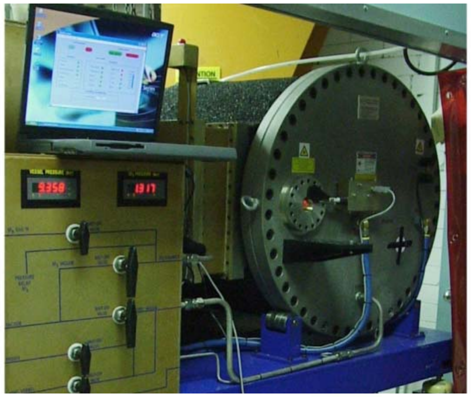
- L-band CW gun (RBT-JLab collaboration)
  - Layer manufacturing process
  - Prototype structures scheduled for testing next year at LLNL and Jlab
  - Design to handle >35 kW cavity avg. power
- Near CW operation possible (~ MHz)
- 7 MeV output energy with additional cells or booster

radiabeam TECHNOLOGIES

ip1

Commercially available high-pressure high-repetition-rate CO_2 lasers



- 10 atm pressure
- 1.5 J per pulse
- 500 Hz repetition rate
- 0.75 kW average power

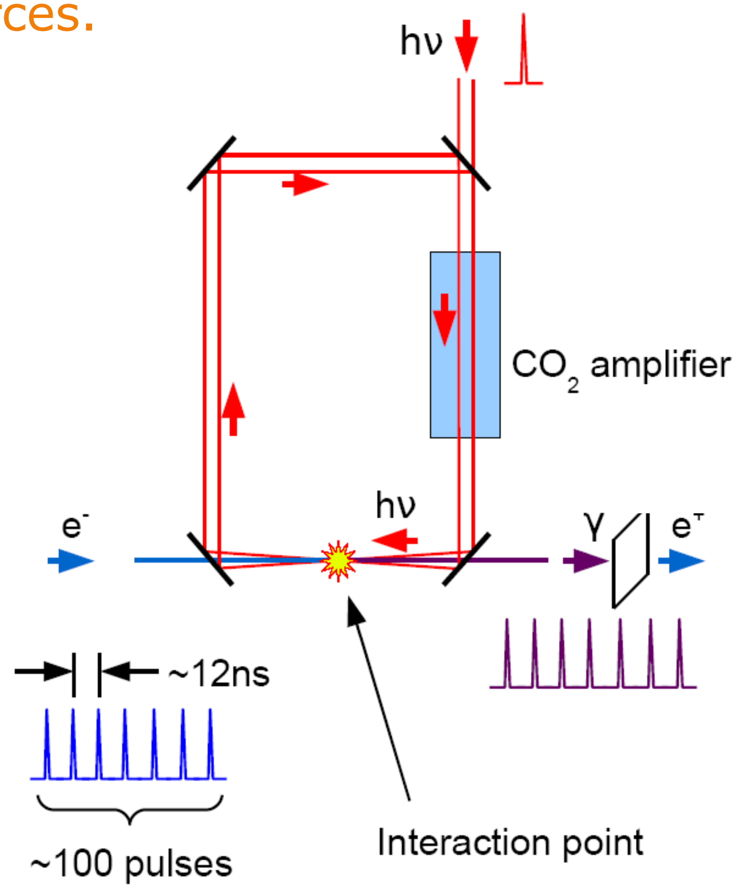
- 5 atm pressure
- 10 J per pulse
- 100 Hz repetition rate
- 1 kW average power

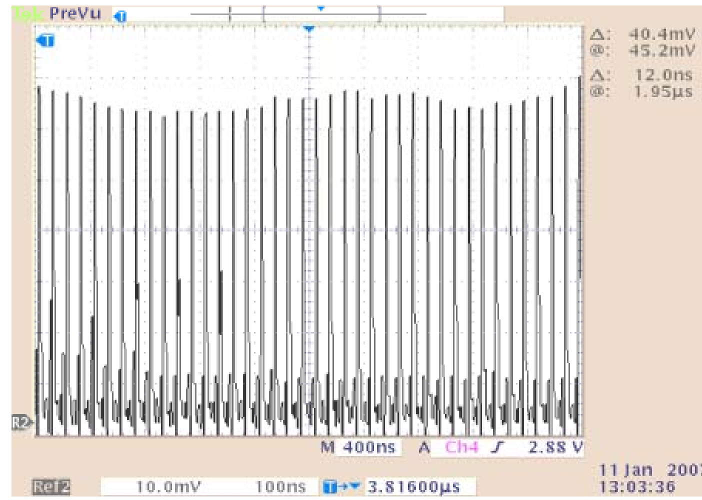
Slide 18

ip1 Here one example of such a laser built by Sopra Co in Paris. This is a high-repetition rate laser operated at 5 atm with a rather decent 5x5 cm discharge cross-section. It is commercially produced as eximer laser, but can be easily converted to CO_2 with such parameters.
Igor Pogorelsky, 12/21/2008

Concept of a high-repetition *x-ray* source

❖A path to compact pico- and femto-second LSS with the peak and average brightness of the order 10^{25} and 10^{17} (s mm^2 mrad^2 0.1%)$^{-1}$ correspondingly - the orders of magnitude higher than modern Light Sources.





•We propose to multiply the Compton γ-source repetition rate by placing it inside the laser cavity.

•V. Yakimenko and I. Pogorelsky, Phys. Rev. ST Accel. Beams **9**, 091001 (2006) .

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Computer simulations

multipass dynamics

- Pressure:

  5atm

- Pulse energy:

  1J

- Pulse length:

  5ps

- Roundtrip time:

  12ns

- Wavelength:

  10.2μm (10R)

- Optical losses:

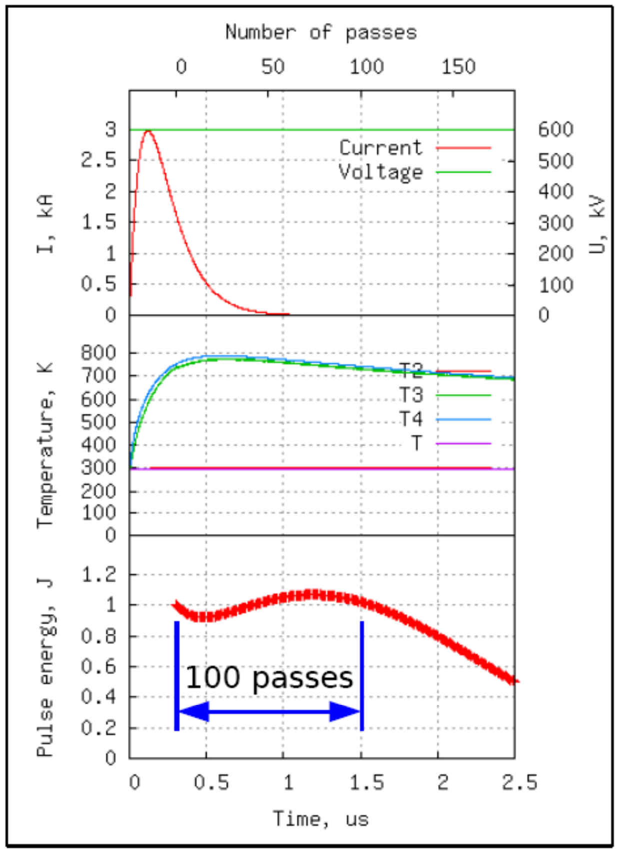
  5% / pass

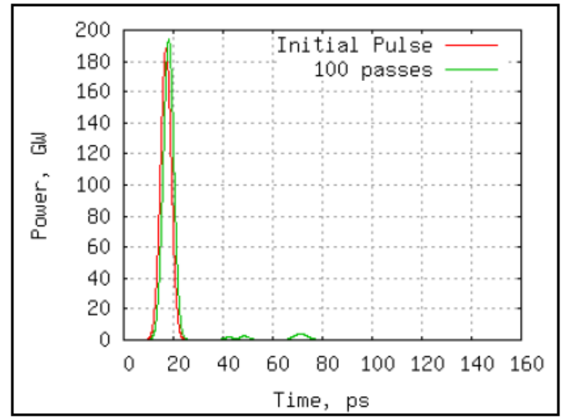
- Gas mixture:

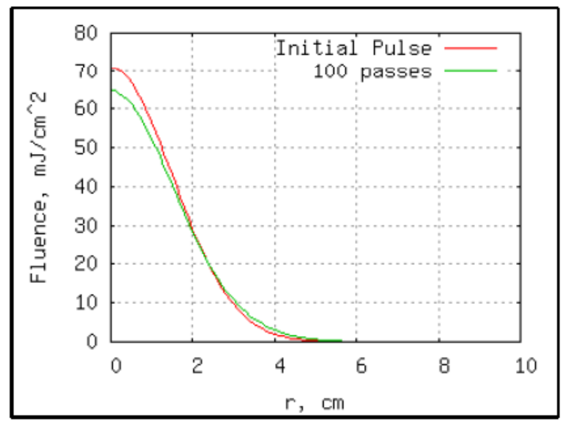
  0.5 : 3 : 6.5

- Isotopes:

  $[O^{16}] : [O^{18}] = 0.8 : 1$







Proposed high-repetition *EUV* source

Initial working point parameters	**EUV L SS**
Electron beam bunch charge	0.6nC
Electron beam energy	10 MeV
Electron and laser bunch lengths, RMS	5psec
Electron beam spot size at IP, RMS	50 µm
Electron beam normalized emittance	2.5 mm-mrad
Electron beam peak current	50 A
Electron beam beta function at IP	2 cm
Laser wavelength	10.6 µm
Laser pulsed energy	2.3 J
Laser beam spot size at IP, RMS	50 µm
Dimensionless laser amplitude	0.30
Laser Rayleigh range	3 mm
Peak X-rays energy	170eV(**7 nm)**
Maximum X-rays flux per interaction	**1×10^9**

Active Collaborators

- *Brookhaven National Laboratory, Accelerator Test Facility, USA*
  M. Polyanskiy, V. Yakimenko
- *RadiaBeam Technologies*
  A. Murokh
- *University of California, Los Angeles, USA*
  O. Williams, J. Rosenzweig
- *INFN, Italy*
  P. Oliva, M. Carpinelli, M. Endrizzi

Conclusions

- *Up to 10^9 x-ray photons/e-bunch have been produced by counter-propagating picosecond CO_2 laser pulses.*
- *Point-like, low-divergence LSS with small energy spread allows for partial spatial and temporal coherence.*
- *Coherence have been demonstrated in experiment on phase-contrast imaging.b*
- *Temporal coherence can be further improved by IFEL micro-bunching.*
- *High-power, up to 1 kHz CO_2 lasers are commercially available.*
- *Repetition rate and average power of LSS can be increase 100-fold by interacting trains of electron bunches inside the regenerative amplifier cavity.*
- *EUV LSS demonstration is in proposal.*